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# From Prototype to Standardization

Five years of LIDAR Anemometry in the Wind Energy Industry

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# Five Years of Lidar Anemometry in the Wind Energy Industry - From Prototype to IEC standard

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# Outline

- **Wind Measurements in Wind Energy**
- Commercially available systems
- The market
- State of the art
- Challenges

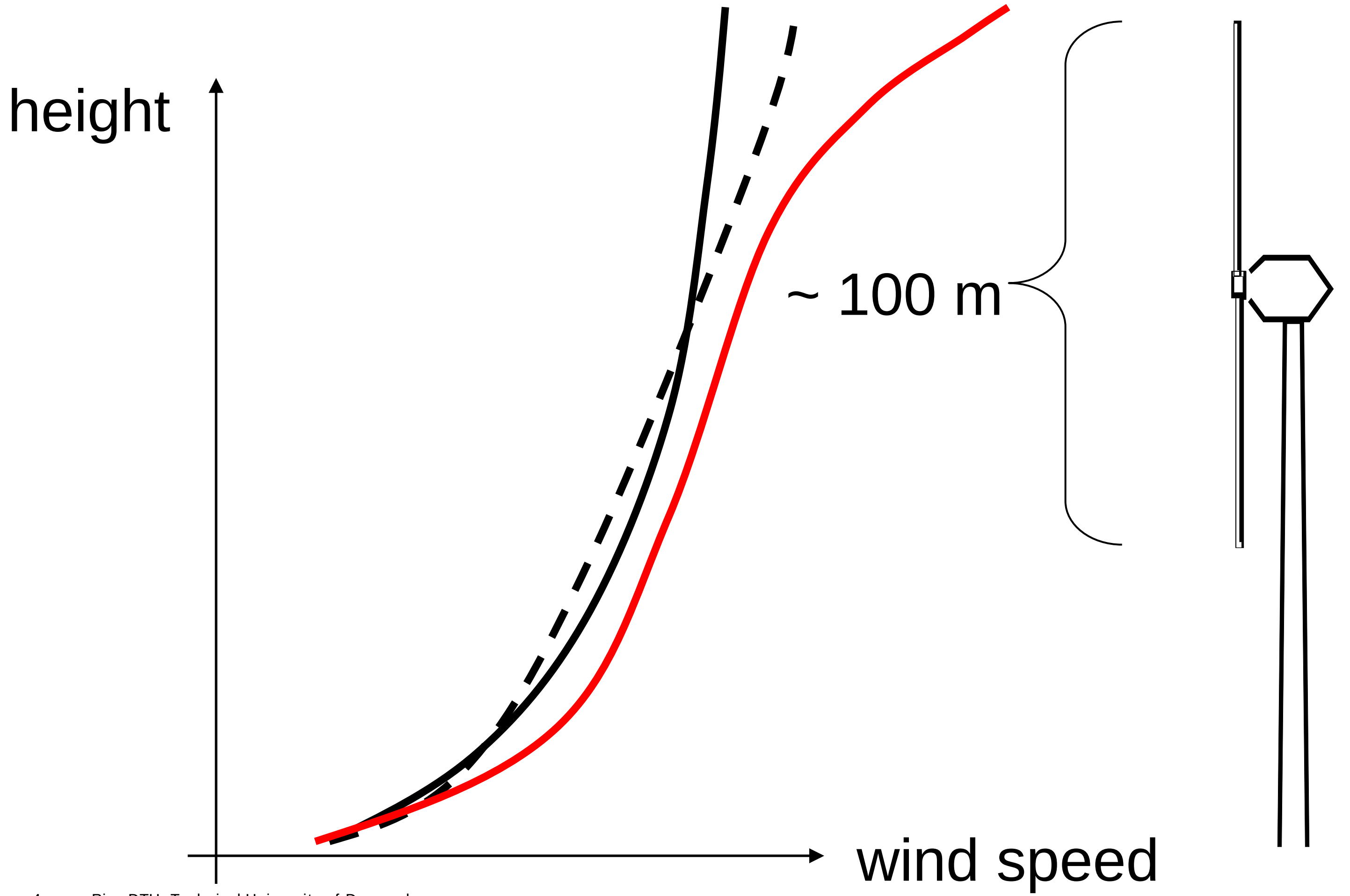
# Wind in Wind Energy

- 10 minute average horizontal wind speed, U
- 10 minute average wind direction
- Turbulence (STDEV in 10 min at 10 Hz)
- Flow angles
- 50 year wind

- For a few months to +1 year
- Offshore, forests, ridges etc
- High availability (>90%)

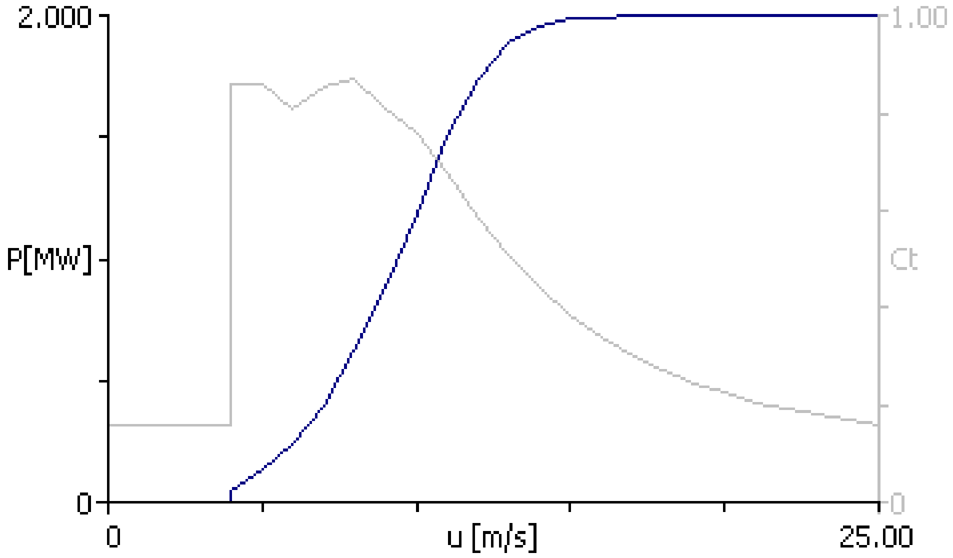
# Wind in Wind Energy

- Today at hub height,  ~ 60-110 m
- Future over rotor area i.e. from 40 to 200 m.



# Power Performance

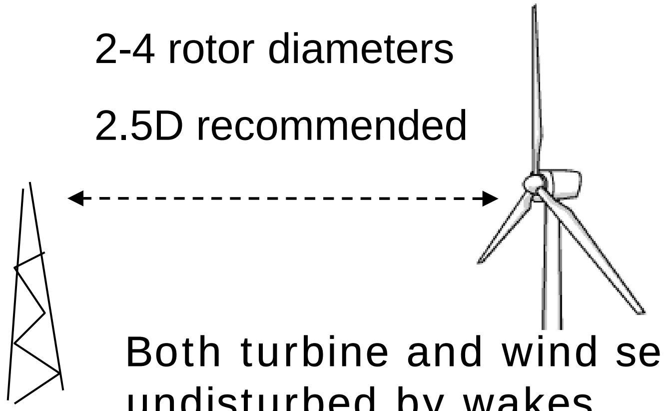
- Measurement of the 10 minute averaged power as a function of the 10 minute wind.




At hub height ±2.5%

2-4 rotor diameters

2.5D recommended



Both turbine and wind sensor undisturbed by wakes.

Simplified : Power = C · ( wind speed )$^3$

In practice : 1% in m/s → 0 – 3% in W → 0 – 3% error in predicted money

# Power Performance

**When**

R&D, turbine optimisation
Turbine specification (comparison between brands, prediction of production)
Acceptance tests once built

+ 180 h for completed test. Free sectors + ~ 4 to 16 m/s wind speeds.
→ 1-2 months in practice.

A lot of money available at this stage, penalties are high for failed acceptance tests

**Demand on sensor**

Cup anemometer better than class 1.7 A
Standard uncertainty : < 0.05 m/s + 0.005*U
Calibration before and after

Wind vane, ± 5° in wind direction

± 2.5% from hub heighth


# Power Performance

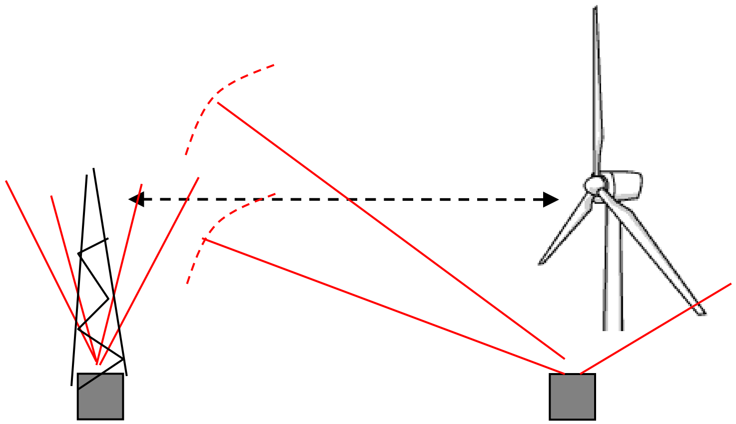
**Lidar anemometer opportunities**

1 Realistic measurement to tip of blade

**More repeatable power performance tests**

IEC standard 61400-12-1 under revision

- Screening of atypical shear and veer
- Normalisation for power law shear, i.e. $U_{eq}$
- Stand alone lidar.



2 Redeployable sensor

**More turbines tested**

- In big farms sometimes only 5% of the turbines are tested.

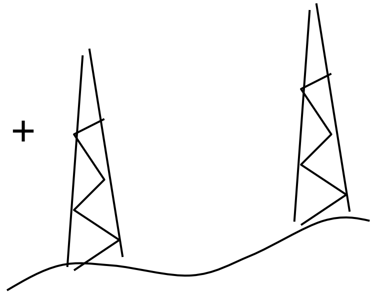
**Challenges**

- Accuracy, less than ± 0.1 m/s in offset and ± 1%, for stand alone option
- ± 1% of hub height vs sample volume FWHM 20 m
- Low standard deviation
- Traceability
- All beams in free wind (narrow cone angles?)

# Wind Resource Assessment

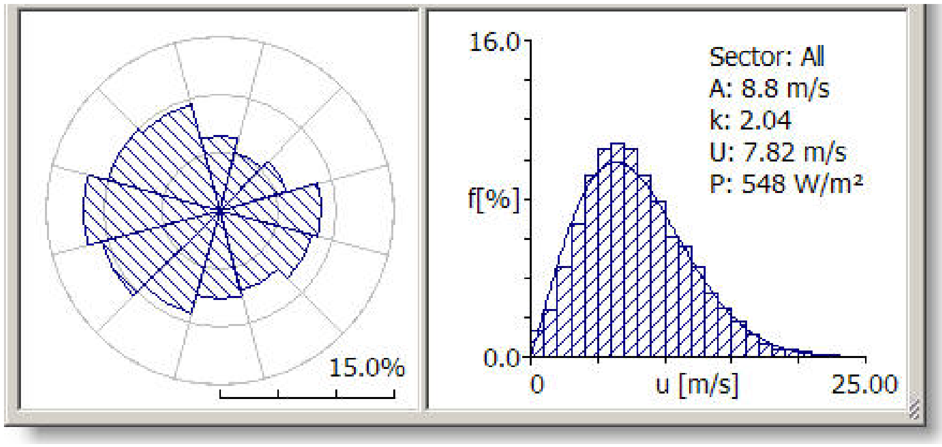
- To obtain building permits and bank loans

Building permit for mast +



+ > 1 year + long term data serie close by

correlate and predict

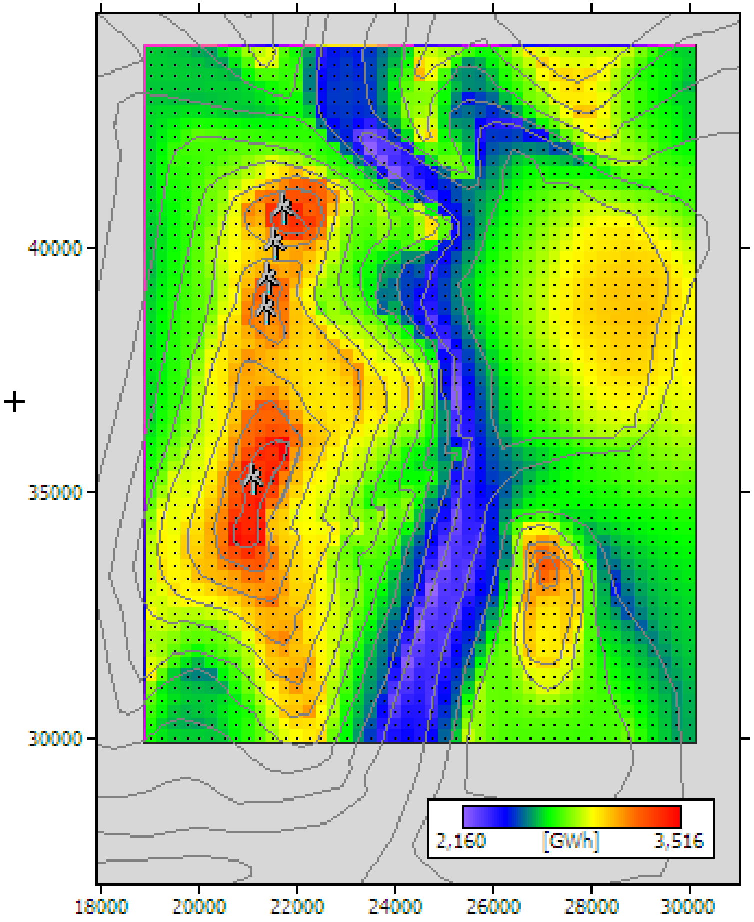



Fitted Weibull distribution

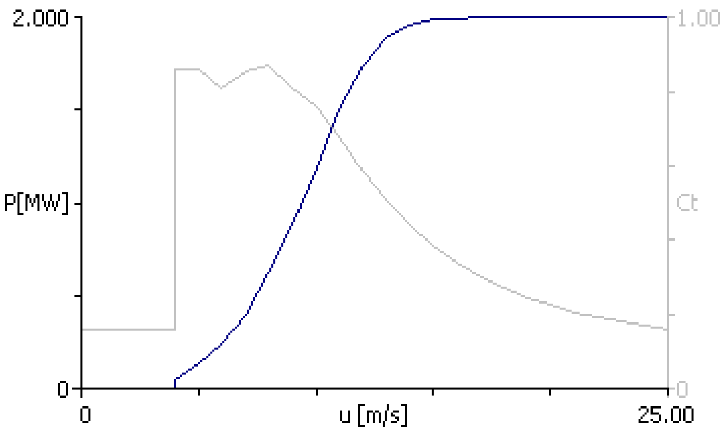
and wind direction rose

# Wind Resource Assessment

Wind climate +



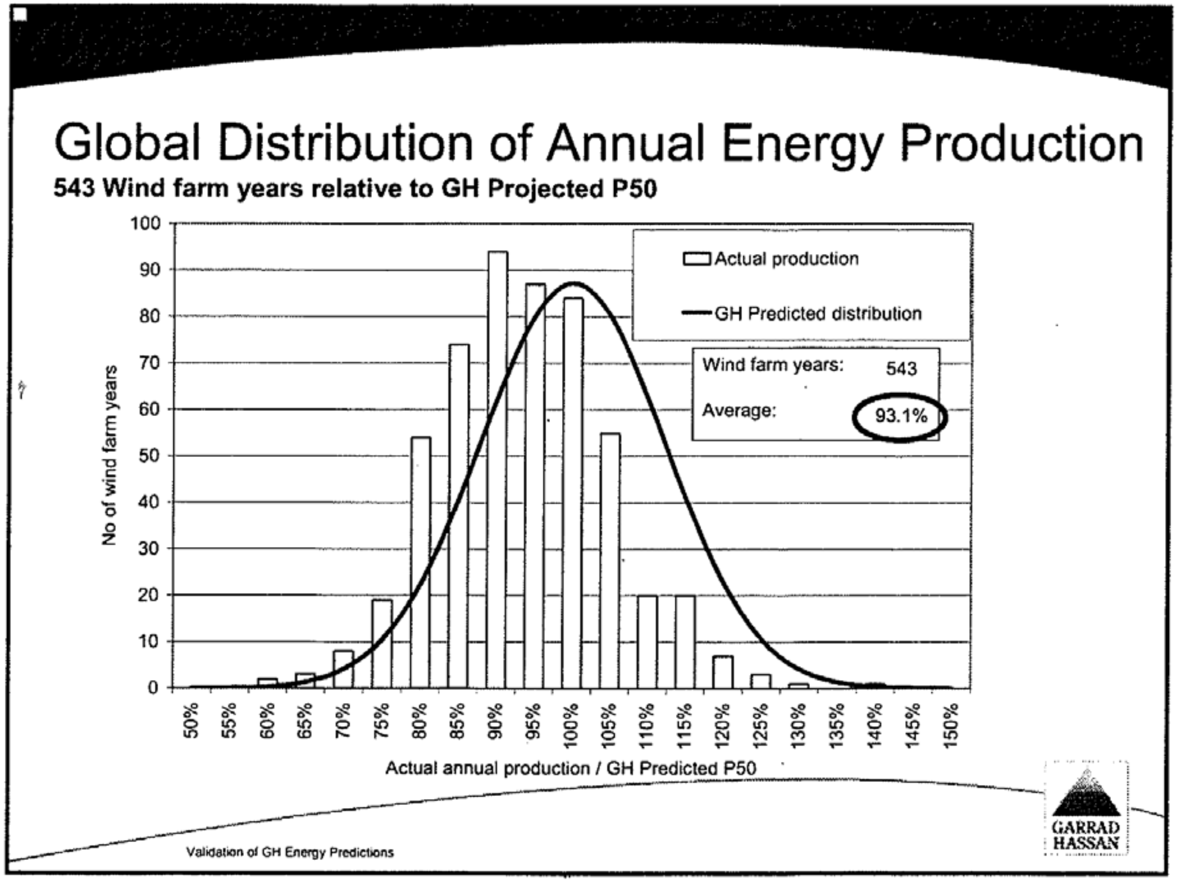

+




Annual Energy Production Estimate

GWh/year

# Wind Resource Assessment




European wind resource map with a 3% margin.

The cost, including measurement campaigns between 2009 and 2015, estimated to 175M€.

US (113 years) 90%

US 2007 (40 years) 89%

Under performance or over estimation ?

Not due to 3% sensor error

# Wind Resource Assessment

No standard but ”bankability”
€ 15 000 in consultancy cost per 2 MW turbine
1MW rated power costs 1.5M€

**Opportunities**

1 No building permits
**Faster start, longer measurement series**

2 Always at hub height
**Reduce bias and STDEV in AEP estimates**

3 Shear and veer data over rotor plane (in future standard ?)
**Less uncertainty in investment**

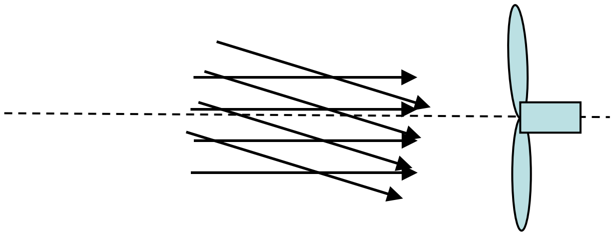
4 Redeployable sensor
**Verification of flow models**

**Challenges**

- Really a need in flat terrain
- Reliabilty (+ 1 year measurements)
- Traceable accuracy
- Availability (> 90%, not correlated with wind speed)

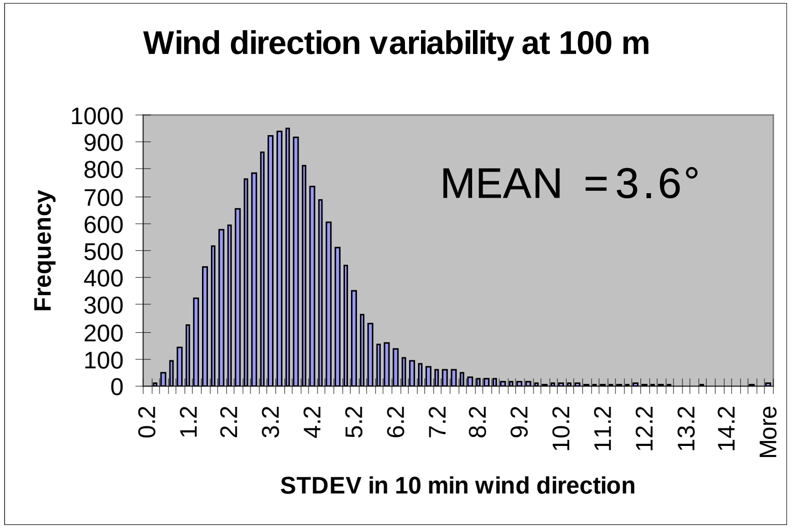
# Turbine control – Yaw

- Optimised power when the turbine faces the wind



Yaw error : Power * $\cos^2(\theta)$

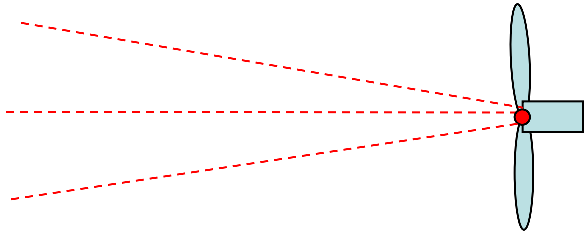
Wind direction variability in a flat site




Wind direction measured on turbine.
Turbine yaws a few times every 10 min to keep aligned with wind direction.
Forecasts of wind direction can help the control rutines.

Catch the wind : ”10% more power”
Risø : ”1-2 % more power”

# Turbine control – Anti Yaw LIDAR



<u>Anti Yaw Lidar</u>

- Few hundred meters upwind
- Accuracy better than 3 degrees

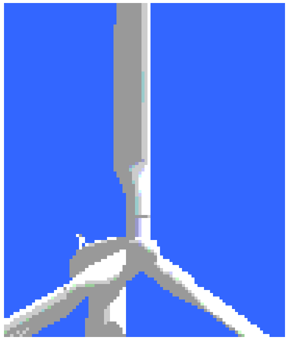
Challenge

How to avoid to misinterpretate turbulence?

# Turbine control – pitch and flaps

Pitch control:

- Collective pitch
- Individual pitch
- Reduce loads 20-30%
- Improve power production
- Similar to the anti yaw lidar but also above and below hub



Flaps:

- Reduce loads
- Improve power production

Flap input

- Angle of attack
- > 2 sensors per wing
- 5 m ahead

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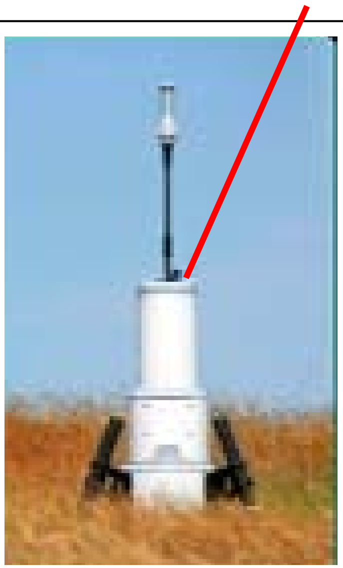
# Zephir – Natural Power Consultants

- Continuous Wave
- Variable focus setting
- VAD Scan 50 points, rotating wedge
- 60° elevation angle
- Cloud correction algorithm
- CE marked – eyesafe IEC 60825-1

- 1.56 µm fiber laser
- 1 W output power
- 7 cm diameter lens
- No offset on LO
- RIN and not head or tail wind
- One LOS every 20 ms
- Frequency resolution 200 kHz

- Measures to 200 m in good conditions
- Minimum range 10 m
- 5 heights sequentially
- 3 sec per height, 1 sec to change
- about 30 measurements at one height in 10 min
- € 125.000



# WindCube – Léosphère

- Range gated
- Fixed focus at ~100 m
- 4 directions, 90° start-stop wedge
- 60° elevation angle
- eyesafe IEC 60825-1

- Measures to 200 m in good conditions
- Minimum range 40 m
- 10 heights in parallel
- 4 sec per full revolution
- about 600 measurements in 10 min (125 completely uncorrelated)
- € 150.000

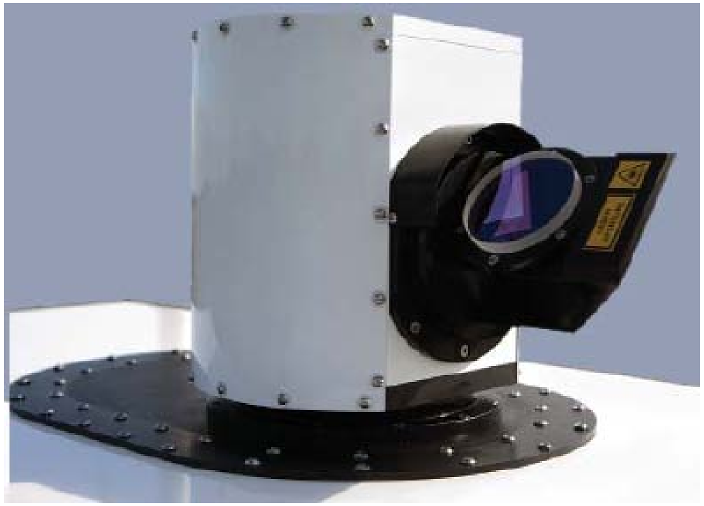
- 1.54 µm
- 200 ns pulse
- 10 µJ
- 20 kHz
- 500 ms to get one LOS velocity
- 10000 averages per LOS
- 5 cm diameter lens
- Offset on LO
- Frequency resolution 5 MHz

# Galion – Sgurr Energy

- Range gated
- Collimated
- two axis scanner head
- eyesafe IEC 60825-1
- 9 month warranty

- Measures to 200 m in good conditions
- 20 sec per full revolution
- 30 uncorrelated meas in 10 min (in 4 direction mode)
- + 30 vertical meas
- € 150.000

- 1.54 µm
- 180 ns pulse
- 10 µJ
- 20 kHz
- 50 mm aperture
- Offset on LO

# Vindicator – Catch The Wind

- Range gated
- Three telescopes
- No moving parts
- Turbine mounted

- Measures to 300 m in good conditions
- Aim price $125.000

- 200 ns pulse

# Competing technologies

**Towers**

Tilt up tower: 1 week assembly € 16.000 + 500 per sensor max 70 m

100 m tower: < €150.000 (Offshore, ·3) 3 months for permit + construction

**SODAR**

3 * Cheaper : $ 40.000 (Lidar € 100.000 -150.000)

5 * Less accurate : σ ~ 0.5 m/s (Windcube σ < 0.1 m/s)

beam bending and low availability at high wind speed

0.1 * power consumption : 10 W (LIDAR> 100 W)

**= 1.5**

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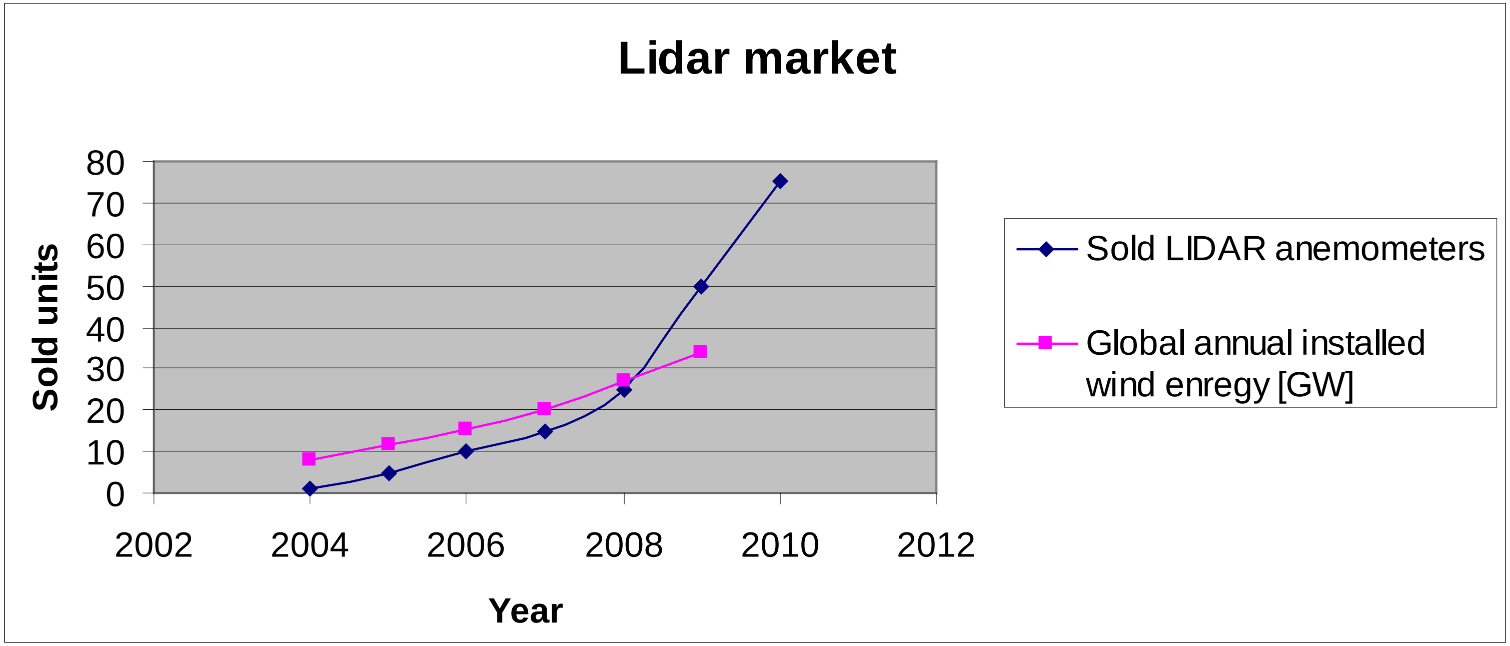
# Lidar market

Estimated cumulative sold lidars:

Zephir ~ 60 systems sold

WindCube ~ 50 systems

Vindicator and Galion < 10 systems




2010 : 75 LIDAR = 10 M€

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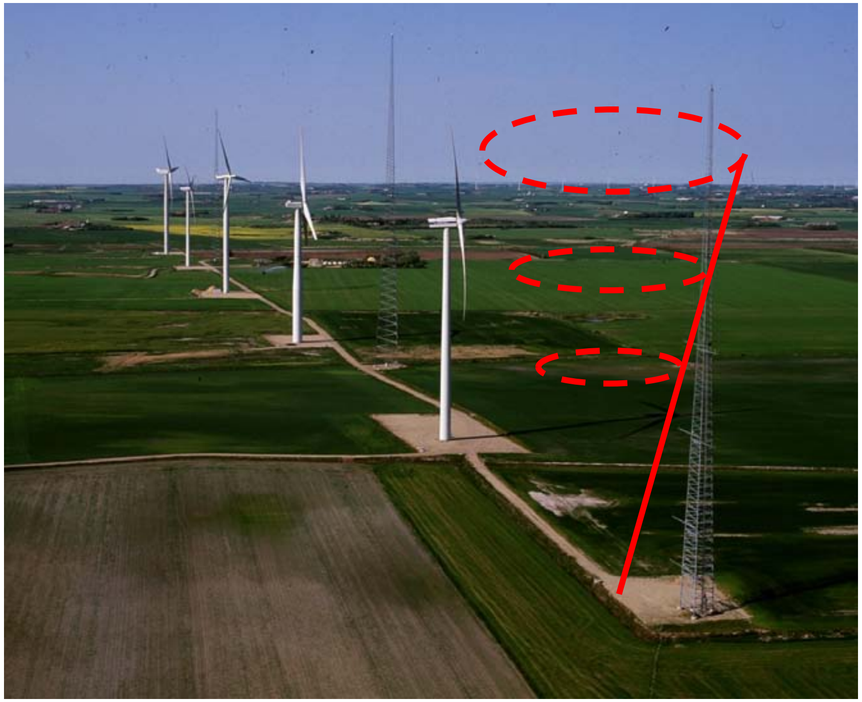
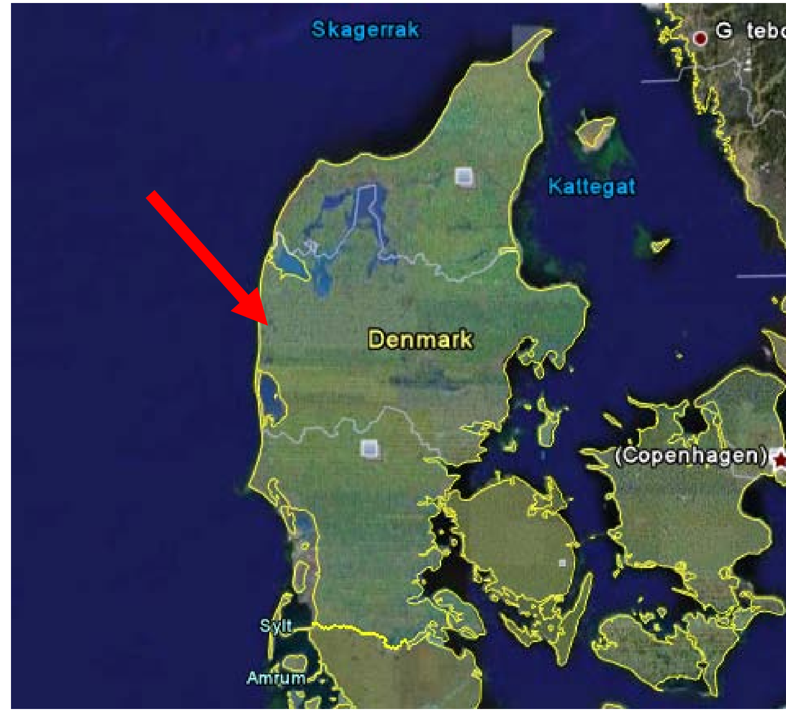
# Testing of LIDAR anemometers in Høvsøre

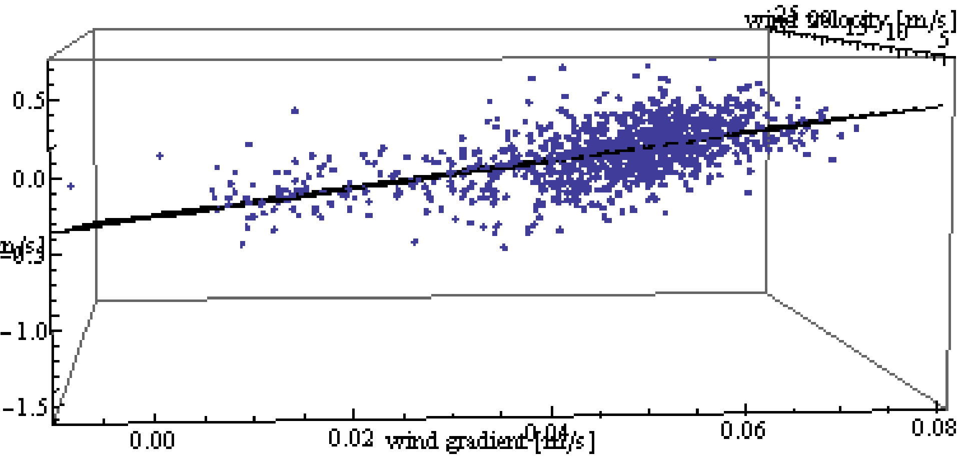




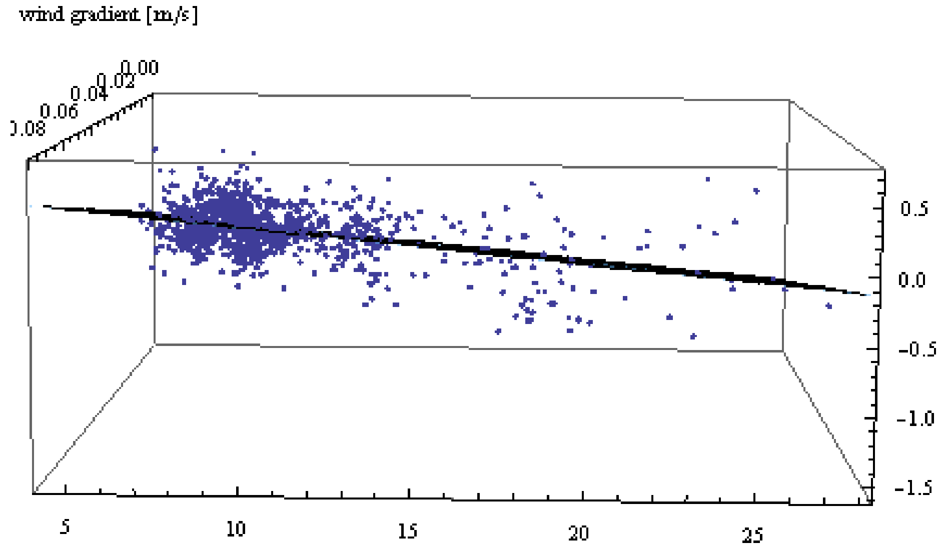

**Høvsøre Large Wind Turbin Test Facility**

- West coast of Denmark, flat terrain, wide range of horisontally homogeneous wind speed.
- Site equipped with rain and cloud sensors
- **15** Zephirs, **15** Windcubes and **1** Gallion tested = 31 lidars
- **90** months of comparison with class 1 cup anemometers @ 40-116 m (160 m)
- Data from 2 other flat sites evaluated

# Error vs Velocity and Shear: 2-parametric linear regression




Wind Gradient [m/s per m]




Wind velocity [m/s]

$$\Delta U = \ 0.163133 \quad 7.94365\,\tilde{x} \quad 0.0248088\,y$$

$$R^2 = 0.33406$$

where

ΔU is lidar - cup [m/s]

x is wind shear [m/s per m]

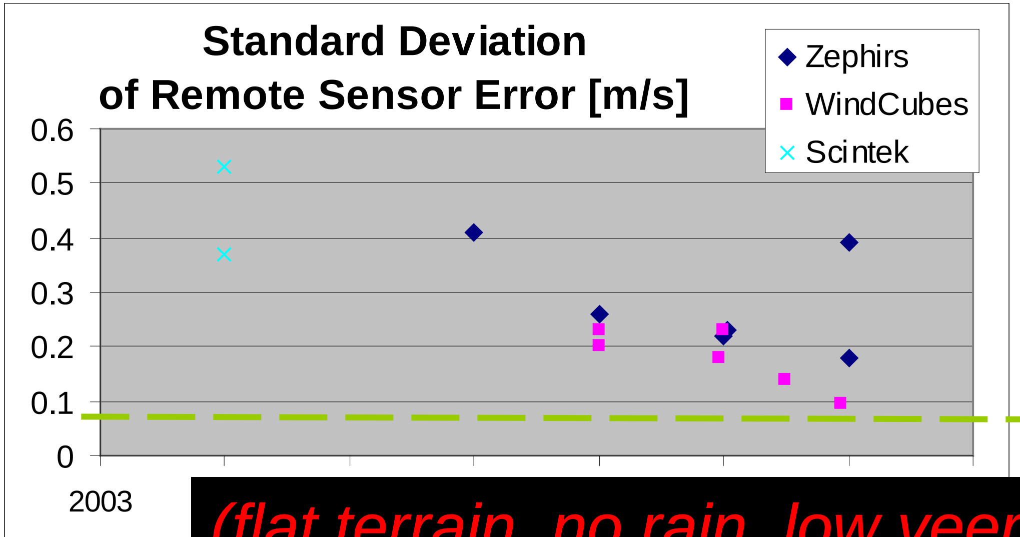
y is wind speed [m/s]

**Estimate**

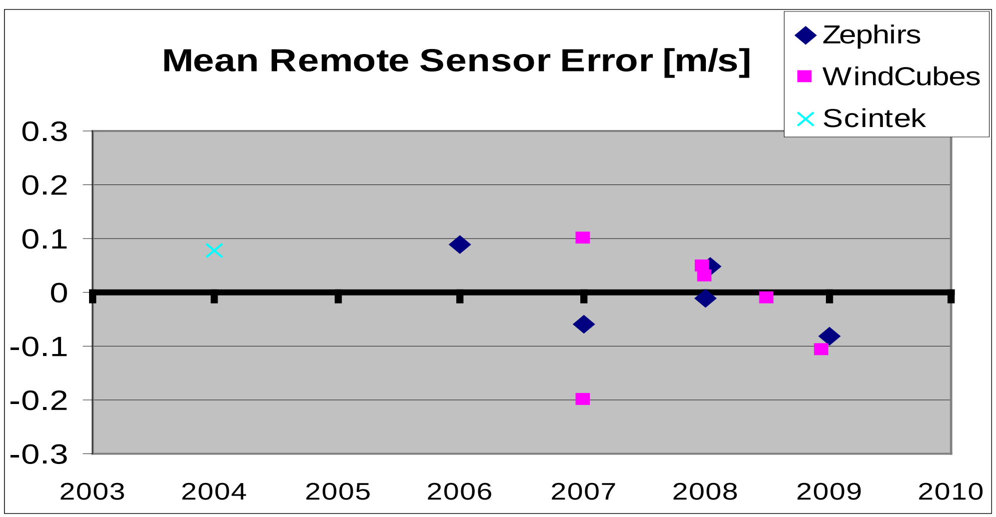
**7.9 m above intended height**

**- 2.48 % mostly due to cone angle**

# Development of Lidar anemometry




*(flat terrain, no rain, low veer, moderate σ)*




**2006: Zephir commercial model introduced. Hardware issues.**

**2007: Ceilometer installed, screening on clouds: positive bias and σ reduced, availability drops. Leosphere introduces Windcube.**

**2008: Cloud correction: availability increases. Cone angle accuracy**

**racy: bias reduced.**

**2008.5: Estimator improved: nonlinear problems solved.**

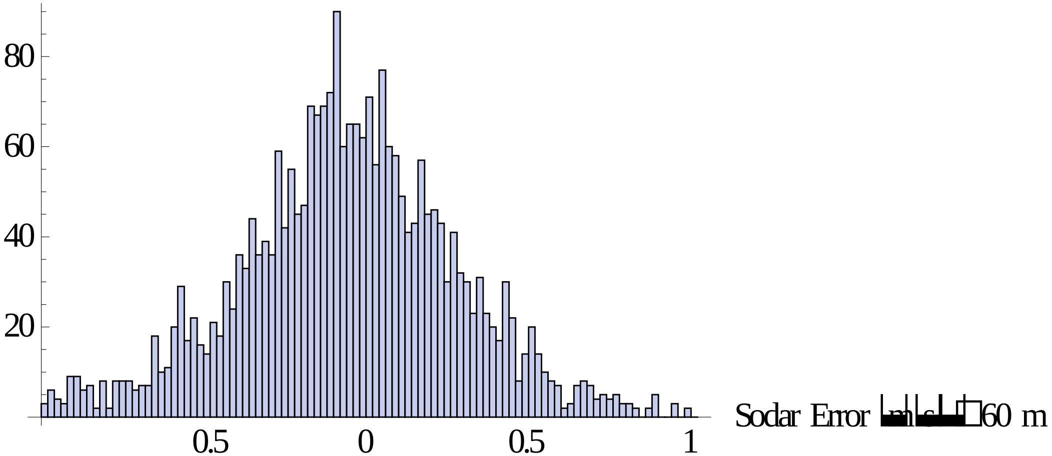
**2009: Improved test conditions, lower RIN. Improved test conditions.**

**Vindicator and Galion commercial**

# Histograms of Remote sensor – cup

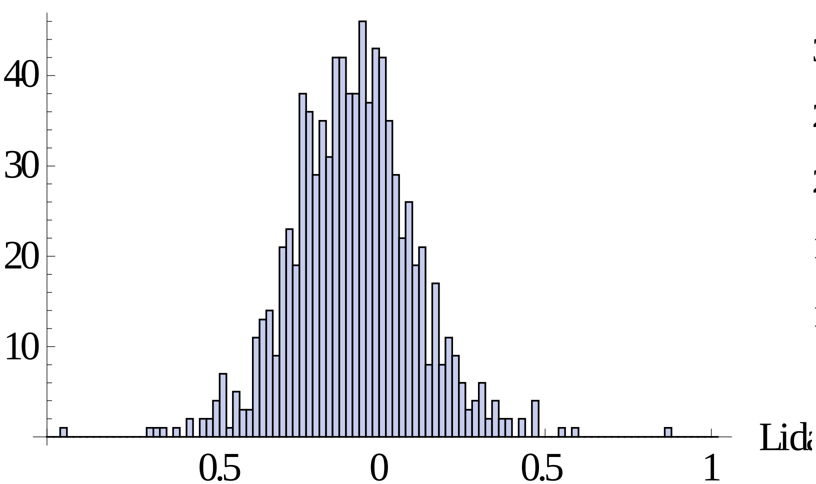
at 60 m

Scintek 2004



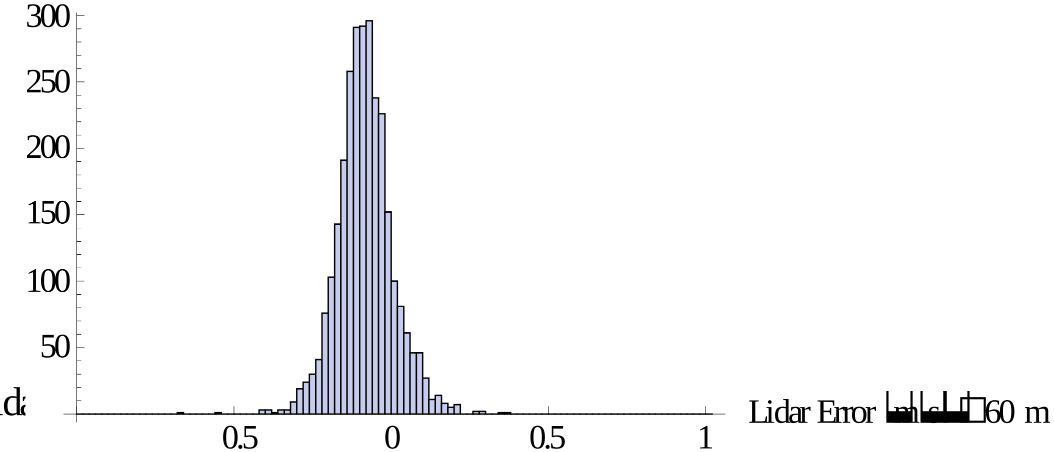

Scintek mean -0.08, STDEV: 0.37

Zephir




Zephir mean -0.08, STDEV: 0.18

Windcube



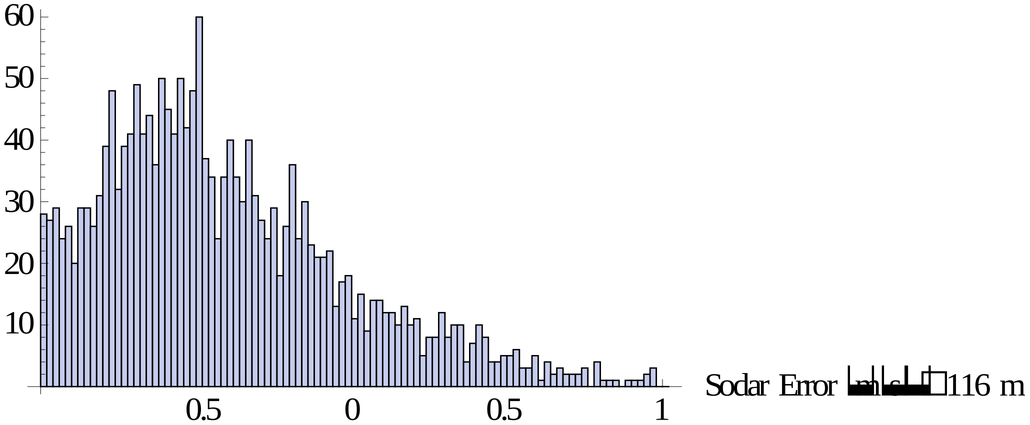

WC mean -0.08, STDEV: 0.09

# Histograms of Remote sensor – cup

at 116 m

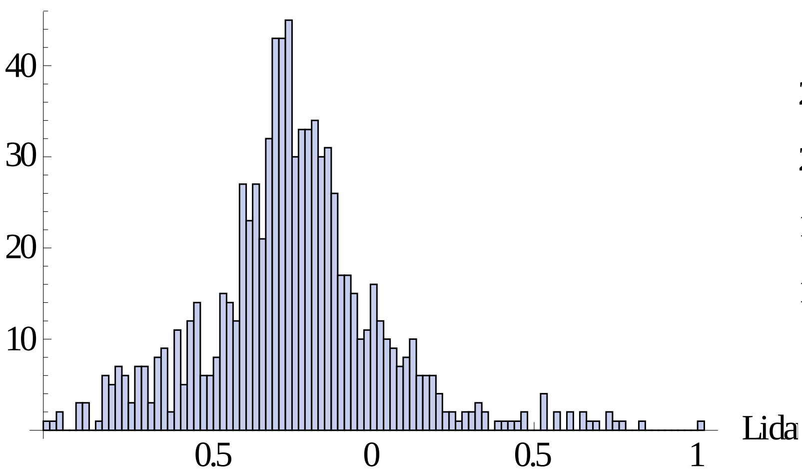
At the coast of
northen Denmark,
>90% availability

Scintek



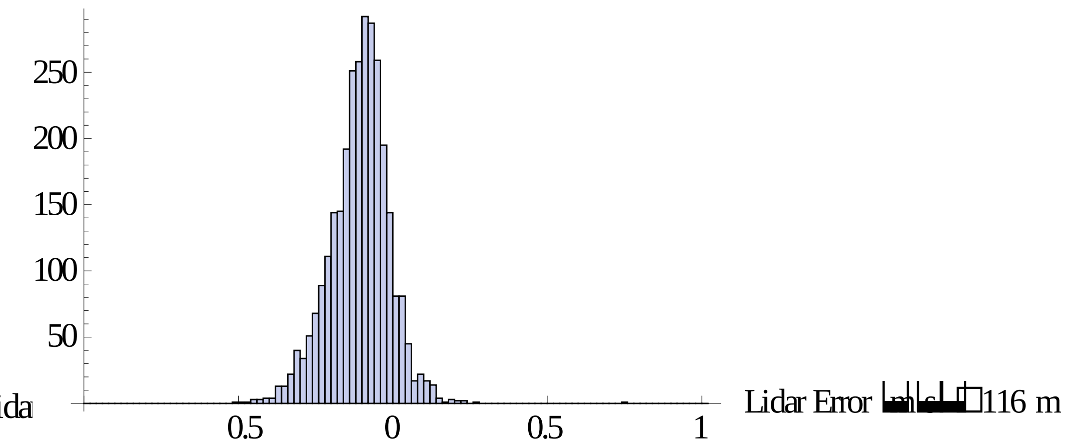

Scintek mean -0.55, STDEV: 0.53

Zephir




Zephir mean -0.29, STDEV: 0.39

Windcube

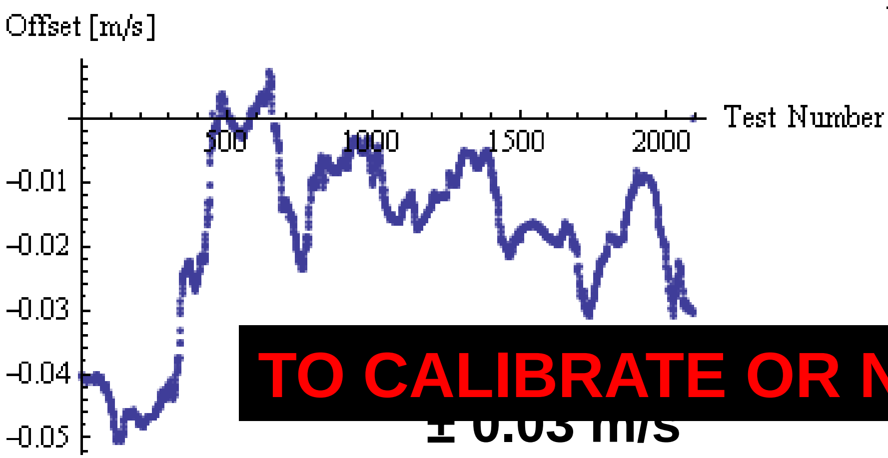



WC mean -0.11, STDEV: 0.10

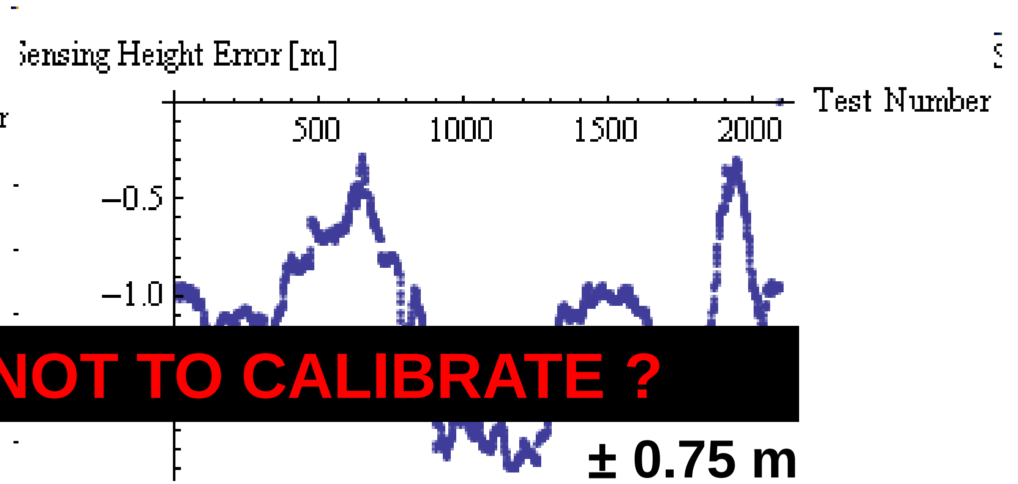
# A good measure of Lidar anemometry accuracy

Estimation of errors for sliding time period

1000 test parameters @ 100 m

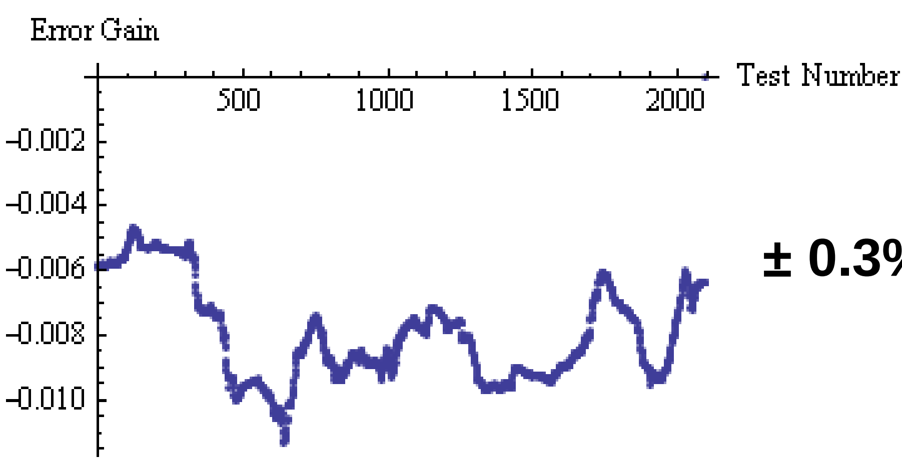



± 0.03 m/s




**TO CALIBRATE OR NOT TO CALIBRATE ?**

± 0.75 m




± 0.3%

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# Challenges

Traceable Accuracy

Best units probably there (flat terrain, no rain, low veer, moderate σ)

Price

/3

Reliability

*3 , i.e. much more reliable

Complex terrain

3 LOS in same space = 3 Lidars with good scanners

Power consumption, roughly 100 W (unheated)

Selfsupporting for a year

# Conclusions

- A need for more and better wind measurements in the wind energy industry

- Need to have in the near term

  - More repeatable Power Performance, new IEC standard will include lidar anemometry

  - Ressource assessment, at hub heigth with lidar beats lower masts, bankable at a few occasions

  - Turbine control, research stage

- 4 commercial suppliers, 10M€ in 2010.

- 0.1 m/s stdev traceable accuracy (Flat terrain, no rain, little veer, moderate turbulence)

- Still key challenges to be met (complex terrain)

# Thank you